2019-01-0365 Published 02 Apr 2019

On-Road and Chassis Dynamometer Evaluation of a Pre-Transmission Parallel PHEV

Miriam Di Russo, Vaibhav Arora, Ronghui Lyu, and Jerry C. Ku Wayne State University

Citation: Di Russo, M., Arora, V., Lyu, R., and Ku, J.C., "On-Road and Chassis Dynamometer Evaluation of a Pre-Transmission Parallel PHEV," SAE Technical Paper 2019-01-0365, 2019, doi:10.4271/2019-01-0365.

Abstract

This paper details the vehicle testing activities performed during the Year 4 of the EcoCAR 3 competition by the Wayne State University team on a Pre-Transmission Parallel PHEV. The paper focuses on two main testing platforms: the chassis dynamometer and the closed-course track (on-road). The focus of the former is to evaluate the emissions and energy consumption associated with different driving scenarios, while the latter has been used to assess the vehicle performance and their impact on the consumer appeal. The paper presents the objectives of each test, the setup accomplished for the different vehicle testing platforms, the results obtained and the comparison with the values expected from simulations. In addition, the impact of the results on the refinement of the control strategies and on the validation of the simulation models are discussed.

The EcoCAR 3 competition challenges sixteen North American universities to re-engineer a 2016 Chevrolet Camaro to reduce its environmental impact without compromising performance and consumer acceptability.

Over the course of Year 4 the Control and Modeling and Simulation team used various simulation platforms to test the control algorithms designed for each operational mode of the vehicle. While Model-in-the-Loop (MIL) and Hardware-in-the-Loop (HIL) environments have been the main focus of Year 2 and Year 3, during this last competition year a considerable amount of time has been spent on chassis dynamometer and closed-course vehicle testing. The control strategies have been tested over a variety of drive cycles to identify the need for refinements and improve the robustness of the algorithms. In addition, the results obtained have been used to validate the components plant model and to support further development of the operational strategies within the non-vehicle platforms.

Introduction

EcoCAR 3 (EC3) is the latest Advanced Vehicle Technology Competition (AVTC) sponsored by the U.S. Department of Energy (DOE) and General Motors (GM) and managed by Argonne National Laboratory (ANL). This four years long competition challenges sixteen universities across North America to re-engineer a 2016 Chevrolet Camaro with the objective of reducing its environmental impact and overall energy consumption while maintaining its performance and safety features.

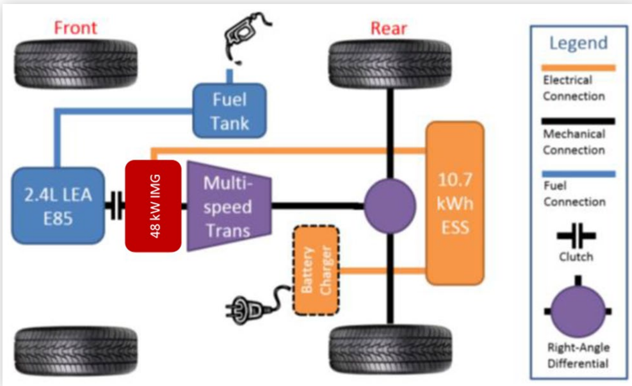
The Wayne State University (WSU) EcoCAR 3 team's mission is to build a fully functional hybrid vehicle that incorporates advanced powertrain technologies, innovation and best practices. This mission serves the team's vision of inspiring, educating and training the future leaders of the automotive industry, exposing them to a broad learning experience that will enhance their intellectual and collaborative capabilities. The goals of the WSU team for the fourth and final year of the EcoCAR 3 competition are as follows:

- Refine and optimize the control strategies that have been designed in previous competition years to maximize the use of grid electricity, further reduce the overall Greenhouse Gas (GHG) Emissions and Energy Consumption (E&EC) and establish an optimal tradeoff between vehicle E&EC and performance.
- Validate the vehicle component plant models using the test data collected over closed course testing and chassis dynamometer testing to support the control strategies and optimization activities.
- Demonstrate that the vehicle is capable of meeting the competition requirements defined in the Vehicle Technical Specifications (VTS) when tested in closed course and chassis dynamometer environment.

The hybrid vehicle architecture selected by the team that best meets the competition and team goals is a Pre-Transmission Parallel (P2-Parallel) Plug-in Hybrid Electric Vehicle (PHEV), shown in Figure 1.

The vehicle powertrain consists of a GM 136 kW 2.4L internal combustion engine (ICE) running on E85 coupled through an electro-hydraulic actuated clutch to a 48kW Bosch Integrated Motor Generator (IMG). The ICE and IMG, located in the engine compartment, are coupled in line to a GM longitudinal automatic 8-speed transmission. The Bosch IMG system is driven by a Bosch INVCON Power Electronics Module (Inverter + DC-DC converter).

FIGURE 1 WSU Hybrid Vehicle Architecture



Located in the trunk is a 10.7 kWh Bosch battery pack, or energy storage system (ESS) consisting of eight lithium-ion battery modules in series, each with 13 cells in series for a pack configuration of 104s1p. The nominal voltage of the system is 390V. A BRUSA on-board charger allows for charging from the grid.

The selected architecture incorporates four different operational modes designed to accomplish different objectives.

Vehicle Operational Modes

Four vehicle operating modes have been implemented within the powertrain control strategies: 1) Charge Depleting (CD) Mode, 2) Charge Sustaining (CS) Mode, 3) Sport Mode and 4) Engine-Only Mode.

The vehicle operates in CD mode when the ESS state of charge (SOC) is above 18%. Two different strategies have been developed within the CD Mode: pure electric (EV) Mode and Blended CD Mode. In pure EV Mode, the ICE is turned off, the engine-disconnect clutch is disengaged, and the torque request from the Hybrid Controller Unit (HCU) is delivered only by the electric propulsion system. In the Blended CD Mode, the clutch is always engaged, and both the ICE and electric motor (EM) provide torque to the wheels. Table 1 provides a brief comparison between the two CD Mode strategies.

Once the ESS SOC drops below the lower limit (18%), the HCU triggers a transition to CS Mode. In this operational mode the bias is towards producing the requested torque with the ICE (clutch engaged). Depending on the specific combination of SOC and driver power request, the electric motor can be used to fulfill part of the torque demand while the engine operates on the most efficient points on the Brake Specific Fuel Consumption (BSFC) map (Motor Drive/Assist), or it can be used as a generator to recharge the ESS in case the SOC is below a certain threshold (Engine Charge). The team investigated and implemented a control strategy that allows the engine to operate in its high efficiency region at the lowest achievable BSFC. The strategy is defined as Optimum Operating Line (OOL) and has been described in detail in [1]. The CS mode strategy is summarized in Figure 2.

The Sport Mode is a performance mode designed to enhance the consumer acceptability in situations that require a high performance vehicle. This performance mode allows both power sources to operate at their full capacities to allow the maximum possible acceleration.

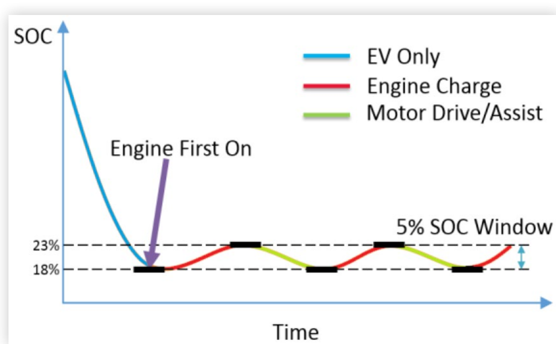
Finally, the Engine-only Mode is used in very specific situations: it is designed to be entered when any component of the electric powertrain is offline due to a failure scenario (Emergency Power Off etc.). In this mode all the torque requests are sent to the ICE and no HV component operation is allowed, including regenerative braking.

During the fourth and final year of the EC3 competition, the WSU team tested the designed control strategies in multiple environments to verify that the vehicle is capable of achieving the VTS targets defined in previous competition years. This has given the team the opportunity to collect component and vehicle operation data to help validate the powertrain simulation models.

TABLE 1 CD Mode strategies comparison

Pure EV Mode (Clutch disengaged)	
Description: In this strategy, the clutch that decouples the engine and the motor is disengaged and the two torque sources are completely disconnected. The engine is always OFF, and the torque required to meet the driver request is fully produced with the electric motor.	
Advantages	**Disadvantages**
No tailpipe emissions during the CD driving portion, Less overall emissions	Complex clutch control, Idling strategy for EM needed to avoid transmission problems, External brake vacuum pump needed, Complex CD-CS transition
CD Blended Mode (Clutch engaged)	
Description: In this strategy, the clutch that decouples the engine and the motor is engaged and acts as a semi-rigid connection between the two torque sources. The engine is always ON and operates on a scaled optimum operating map. The bias is toward producing the majority of the torque to meet the driver request with the electric motor.	
Advantages	**Disadvantages**
Simple Strategy, No clutch control, No need to realize “idling motor” to avoid transmission problems, No need of external brake vacuum pump, Smoother CD-CD transition (simple torque blending)	Increased overall emissions, Reduced Flexibility, Engine braking present in regenerative braking mode

FIGURE 2 CS Mode vehicle operation associated with SOC



Depending on the level of maturity of the control software and on the available facilities, three main testing environments have supported the refinement of the control code strategies: On-hoist, Chassis Dynamometer and Closed-course tracks. Table 2 summarizes the EC3 Year 4 testing activities:

The On-hoist tests are used to verify static functionalities that do not require the vehicle to be in motion. This type of test has been used extensively when developing the handshake strategies between the team's HCU and the powertrain component Electronic Control Units (ECU). In addition, the On-hoist testing has been the main platform used to verify the correct implementation of the designed detection and mitigation diagnostic strategies. This step has been crucial in the case of the engine-disconnect clutch, to ensure that safe operations could be achieved.

The Closed-course track available to the team within the WSU campus, presented many restrictions due to the limited maximum speed (< 30 mph) and it has been used mainly for low-speed testing. The On-hoist and campus Closed-course (low-speed) testing environments are reported here for completeness but are not in the scope of this discussion.

During EC3 Year 4, the team had the opportunity to test the vehicle on a two-wheel chassis dynamometer at the Transportation Research Center (TRC) Emission Laboratory in East Liberty, Ohio. The tests conducted, which will be described in detail later in the paper, focused on the evaluation of the vehicle fuel and energy consumption, emissions,

TABLE 2 Year 4 Testing Activities

Testing Method	Location	Main parameters tested
On-Hoist	Team Garage, WSU Campus	Static functionalities
Campus Closed-course Track	WSU Campus	Shakedown
Chassis Dynamometer	TRC Emission Laboratory, OH	Emissions, Energy Consumption
Drag-racing Track	Milan, MI	Acceleration, Braking, Handling

FIGURE 3 WSU vehicle during chassis dyno testing

battery charging and control system functions while operating in CD and CS modes. By testing the vehicle over the same known drive cycle for both the CD Blended and CS strategies, the team was able to investigate the impact of each strategy on the vehicle emissions and energy consumption. In addition, the engine optimization strategy designed within the CS Mode was tested to verify its impact on engine fuel consumption and emissions. The data collected enabled a thorough analysis of vehicle operations. Note that the EV-only mode has been tested but the transition to the CS Mode was triggered artificially since the clutch control algorithm was not fully developed at the time of the test. The results of the EV-only test are not in the scope of this discussion and are presented in a dedicated paper.

Finally, the acceleration, braking and handling performance of the WSU vehicle have been tested on a dedicated drag-racing track. The results of the tests have been used to refine the Sport Mode control algorithms to enhance the consumer appeal and guarantee that the VTS targets can be meet.

The setup, the objectives, as well as the main parameters monitored for each test are detailed in the next section.

Vehicle Testing Setup

Chassis Dynamometer Testing

Test Setup The WSU vehicle has been tested on a Horiba two-wheel chassis dynamometer within the Emission Laboratory at TRC. The dynamometer is an in-ground installation with 48" diameter rolls protruding above the surface to interface with the vehicle wheels. A direct current motor is supplemented to simulate the vehicle inertia up to 6,000 lbs. as well as to simulate aerodynamic drag, rolling resistance and grade loading [2].

The two-wheel dynamometer room is equipped with a fan whose speed was set to match that of the vehicle to test the effectiveness of the re-designed cooling system. The room temperature has been set up to be constant at 75° F with a 31% humidity level.

The stock Camaro coast down coefficients have been applied during the dynamometer test setup. These coefficients are GM confidential and cannot be divulged. The test weight for the vehicle has been set to 1716 kg and the tire pressure to 35 psi.

Data Acquisition The two-wheel chassis dynamometer uses a full-flow constant volume sampling dilution tunnel system. The vehicle exhaust is transferred through an insulated pipe into the dilution tunnel. The diluted gaseous emissions have been analyzed through the exhaust emission analyzer available in the dyno room.

A Vector GL1000 Compact Logger has been used to collect the signals from the vehicle stock high-speed (HS) Controller Area Network (CAN) bus. The logger has been mounted below the driver seat, and continuously monitored during the test. The data has been logged at a rate of 1 Hz. Signals from the other two HS CAN buses available on the vehicle network have been collected using a 2-channel Vector CANCase XL. In addition, the most important feedbacks from the vehicle component (CAN, analog and digital), and from the component ECUs have been monitored and recorded through ETAS INCA user interface.

An OBD scan tool has been used to read and record other communication parameters from the CAN buses used by the Camaro powertrain, and to verify the presence of any Diagnostic Trouble Codes (DTC).

Tests Conducted To properly evaluate the charge-depletion characteristics, the amount of fuel displacement, and the energy used, the following tests have been conducted:

1. Emission and Energy Consumption (EEC) On-Road Cycle: this drive cycle is a combination of city and highway driving and is shown in Figure 4. It is used within the EcoCAR competition to evaluate the performance of the vehicle in terms of emissions and energy consumption.

This test has been repeated twice over two different testing sessions to evaluate a Basic CS strategy and an Optimized CS strategy and compare the results between the two tests. A detailed analysis of the results is provided in the Results section. Both tests included two consecutive repetitions of the EEC On-Road cycle. The two tests were conducted using identical dyno setup, however the initial state of charge of the battery differs by 4%. Table 3 provides an overview of the tests conducted over the EEC On-Road drive cycle.

2. Urban Dynamometer Driving Schedule (UDDS) Cycle: this test has been conducted entirely in CS Mode. Table 4 provides an overview of the test objectives and main parameters. The results of this test are not shown in this paper.

All the tests have been conducted with a TRC employee as the driver and a student as passenger. The results obtained for each test are presented and discussed in the Results section.

TABLE 3 EEC On-Road drive test overview

Emissions and Energy Consumption (EEC) On-Road Cycle	
Test Objectives : • Evaluate the CD range • Determine vehicle fuel and energy consumption • Evaluate the efficiency of the ICE/electrical powertrain • Capture an engine cold start event • Collect emission data • Verify CD and CS Mode algorithm robustness	
Main Data Monitored	**Test Impact**
• CD Range (miles) • El. Energy Consumption (Wh/mi) • Fuel Consumption (gal) • ESS charge/discharge under continuous load • HC, NOx, CO (g)	• CD/CS Mode torque distribution strategy optimization • Energy management optimization • Plant models validation

TABLE 4 UDDS drive test overview

Urban Dynamometer Driving Schedule (UDDS) Cycle	
Test Objectives : • Evaluate the effectiveness of engine optimal operation strategy • Troubleshoot CS strategy for motoring and braking • Calibrate ESS charging/discharging limits • Calibrate negative torque during regen braking	
Main Data Monitored	**Test Impact**
• El. Energy Consumption (Wh/mi) • Fuel Consumption (gal) • Engine Efficiency (%) • HC, NOx, CO (g)	• CS Mode refinement • ESS dynamics charge/discharge limits calibration • Regen braking strategy refinement

On-Road (Closed-course) Testing

Test Setup During Year 4 of the EcoCAR 3 competition the WSU team had the opportunity to conduct Closed-course testing on a NHRA drag-racing track located 50 miles from the WSU campus. The two lanes track consists of a 0.6 mi stretch, which is ideal to test vehicle performance.

FIGURE 4 EEC On-Road drive cycle trace

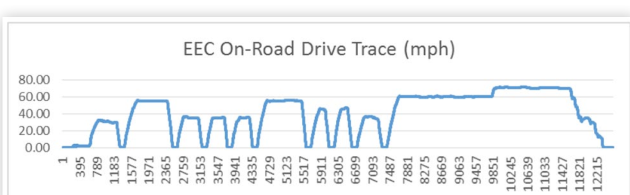


FIGURE 5 Milan drag-racing track

The external temperature on the day of the test was 10 deg. C. The pressure of the tire was measured to be 35 psi. Each test has been conducted with a WSU student as the driver and a WSU student as passenger. The ESS battery was fully charged (95%) before the beginning of the tests.

The main objective of the tests conducted at this location was the characterization of the vehicle behavior in those situations that require high performance and rapid response, to

FIGURE 6 WSU vehicle at Milan drag-racing track

meet the driver requests and enhance the consumer appeal. All the tests except the "Handling" have been conducted selecting the team designed "Sport Mode" as operating mode. The control strategy behind this mode has been discussed in the Vehicle Operational Modes section. The driver can enter this operating mode by pressing the stock Mode Selection switch, located in the vehicle center console. Upon the activation of this mode the driver will receive a visual confirmation on the cluster bottom right corner that the mode has been entered correctly.

Data Acquisition The same data acquisition systems used for the dynamometer testing have been used for the Closed-course testing. The Vector logger has been used to collect the signals from the vehicle stock HS CAN bus, while the Vector CANCase XL collected the signals transmitted over the non-stock vehicle CAN buses. Feedbacks from the vehicle components (CAN, analog and digital), and from the component ECUs have been monitored and recorded using the ETAS INCA user interface.

Tests Conducted The configuration of the drag track is ideally suited to test the vehicle performance and validate the following VTS parameters: 1) IVM-60 mph acceleration time, 2) 50-70 mph passing time, 3) 60-0 mph braking distance and 4) vehicle handling.

Four tests have been conducted to evaluate the four VTS parameters listed above. As mentioned, all the tests, except for the Handling, have been conducted using the Sport Mode. For this specific mode the team has designed a more aggressive pedal map (APP vs. Torque Request map) to enhance the response of the vehicle. The map required extensive calibration to eliminate or reduce the amount of wheel slip during the launch stage. Table 5. to Table 7 summarize the objectives and main signals monitored during each test.

For the IVM-60 mph test the vehicle started at 0 mph and was accelerated at wide open throttle to 65 mph (to ensure that the top speed was reached). This test has been repeated three times and the results obtained (presented later) have been averaged.

The braking test (60-0 mph test) is conducted by accelerating the vehicle to 60 mph, maintaining the speed for 5 seconds and then fully pressing the brake pedal (BPP=100%)

TABLE 5 0-60 mph/50-70 mph acceleration test overview

IVM - 60 MPH/ 50-70 MPH Test	
Test Objectives : • Evaluate IVM-60 mph acceleration time • Evaluate 50-70 mph acceleration time • Characterize ICE and EM torque delivery when APP=100% • Characterize transmission shifting when APP=100% • Calibrate ICE/EM torque uprate and de-rate limits • Validate wheel slip model*	
Main Data Monitored	**Test Impact**
• IVM-60 mph time (sec) • Engine Torque (Nm) • Motor Torque (Nm) • Transmission Gear	• Sports Mode torque distribution strategy refinement • Wheel slip limits refinement* • Pedal map calibration

* for the IVM-60 mph test

TABLE 6 60-0 mph Acceleration test overview

60-0 MPH (Braking)Test	
Test Objectives : • Evaluate 60-0 mph braking distance • Characterize transmission shifting when BPP=100% • Calibrate Regenerative braking strategy and limitations	
Main Data Monitored	**Test Impact**
• Braking distance (mi) • Transmission Gear • Battery current (A)	• Sports Mode braking strategy refinement • Battery limit management strategy refinement

TABLE 7 Handling test overview

Handling Test	
Test Objectives : • Evaluate vehicle handling with new powertrain mass and weight distribution • Evaluate need for tires replacement, spring and/or sway bar redesign	
Main Data Monitored	**Test Impact**
• Yaw Rate • Lateral acceleration (g's)	• Tires selection • Spring effectiveness • Sway bar effectiveness

until the vehicle comes to a complete stop. The regenerative braking was enabled during the test.

The lateral skid pad test (Handling test) was conducted to determine the maximum speed that the vehicle can achieve in a cornering situation. The test has been performed on an 80 feet constant radius circle on a paved road. A cone marked the start/stop line. Starting at the cone the speed was increased as the driver turns around the circle until the steering angle cannot be maintained. The test was performed both in clockwise and counter-clockwise directions. The tires were warmed up using a sinusoidal steering pattern before the test was started.

While during the competition dynamic events the vehicle displacement, speed and lateral acceleration are obtained through an external data acquisition system, in this case the vehicle was not equipped with any additional sensors. The data used for the analysis have been obtained through the CAN loggers mounted in the vehicle.

The results of each test are presented and discussed in the following section.

Results

Chassis Dynamometer Testing Results

As mentioned in the Vehicle Testing Setup section, during the Year 4 of competition the team had the opportunity to use the TRC facilities to test the vehicle under pre-determined drive cycles on a chassis dynamometer equipped with emission measurement systems.

Two test sessions were conducted over the course of three months. The results of the first session were used to refine the torque distribution and energy management strategies. The improved strategies were analyzed during the second testing session over the same drive cycle, and under the same setup conditions.

First Testing Session: Basic CS Strategy Beginning from a cold start, and with a SOC of 94.6% the team vehicle was tested in Blended CD Mode (clutch engaged) and Basic CS mode over the EC3 Emission and Energy Consumption (EEC) drive cycle, shown in Figure 4. The CS Mode strategy tested was a pure “Charge Sustaining” strategy: the engine was operated on its OOL to meet the driver torque requests. The extra torque from the engine (if available) was used to re-charge the ESS using the EM as a generator if the ESS SOC depleted below the pre-determined lower limit (18%). The “Engine Charge” and “Motor Assist” strategies [1] were not integrated into the HCU algorithm at the time of this first test. Both strategies have been discussed into more detail in the Vehicle Operating Modes section. Figure 7 shows the two consecutive EEC cycles driven during this first test. The ESS SOC depletion over the cycles is reported along with the ICE fuel consumption.

Note that the data has been acquired with a sample time of 10 Hz. Therefore, the total time of the test represented on the x-axis of the graph is approximatively 1 hour.

In total 14 miles were driven in CD Mode. The CD strategy tested is a Blended “Motor Dominant” strategy. This is evident by observing the torque distribution between EM and ICE in Figure 8. The electric motor is the main torque source within this mode, and the negative torque observed is the result of the regenerative braking events. Once the vehicle fully depletes the ESS usable energy (lower SOC limit is set to 18%) it automatically transitions to CS Mode. For this test the CS Mode was not triggered by a SOC depletion below the limit, instead it was triggered using one of the competition required switches, located in the vehicle. When the switch is pressed the ESS SOC is artificially interpreted by the HCU as the lower limit of the SOC window, and the CD-CS transition is activated. Within the CS Mode strategy the ICE is the main torque source, while the EM operates as a generator to recharge the ESS.

As shown in Figure 8, the lower limit of the negative torque to the motor was modified during the test from -80 Nm to -40 Nm to avoid engine stalling. The charging limits have been calibrated and refined after this test to allow for different level of negative torque for different values of

FIGURE 7 WSU vehicle driven on EEC repeated drive cycles – Basic CS Strategy

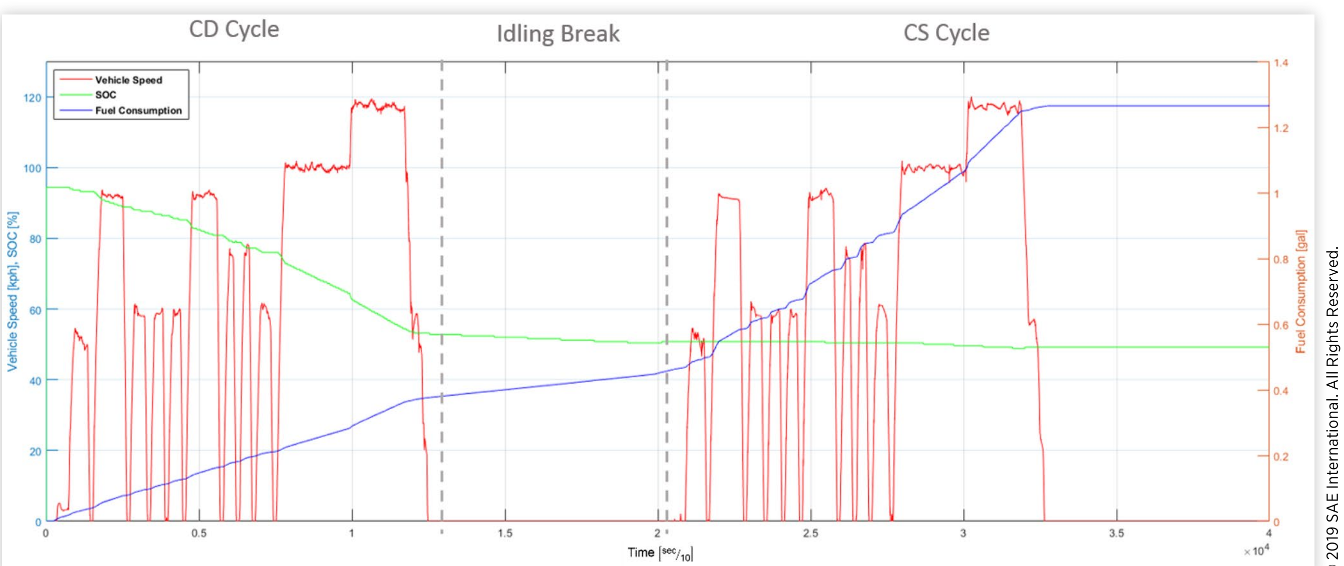
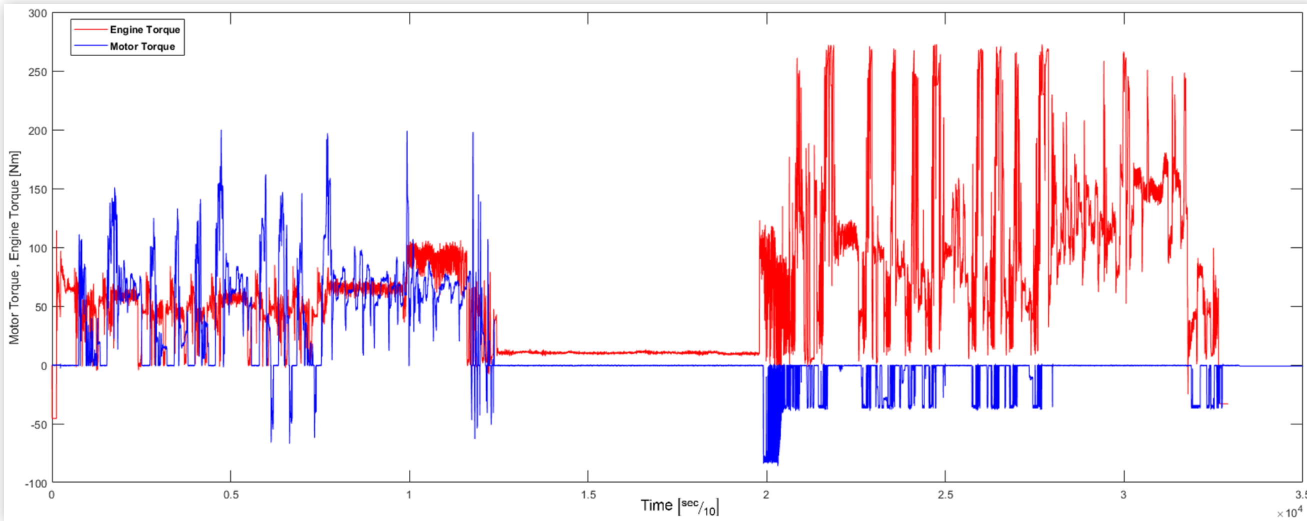


FIGURE 8 EM and ICE Torque for EEC repeated drive cycles – Basic CS Strategy



EM speed and vehicle speed. Table 8 shows the VTS results for the two consecutive EEC cycles driven using the Basic CS Strategy.

The values shown in Table 9 are obtained by post processing the 10 Hz modal data acquired through the chassis dynamometer instrumentation.

TABLE 8 Calculated VTS for EEC repeated drive cycles – Basic CS Strategy

Specification	Target	Actual Value
Fuel Consumption	1.18 gal	1.27 gal
Total Miles Driven	30 mi	28.7 mi
CD Mode Range	26 mi	14.1 mi*
Utility Factor (UF)	N/A	0.302
CD Mode Total Energy Consumption	497 Wh/km	545 Wh/km
CD Mode Electrical Energy Consumption	137 Wh/km	159 Wh/km
CD Mode Fuel Energy Consumption	360 Wh/km	386 Wh/km
CS Mode Total Energy Consumption	712 Wh/km	917 Wh/km
CS Mode Fuel Energy Consumption	700 Wh/km	904 Wh/km
CS Mode Electric Energy Consumption	11.7 Wh/km	13 Wh/km
UF-Weighted Total Energy Consumption	23 mpgge	17.7 mpgge
UF-Weighted Fuel Energy Consumption	450 Wh/km	747 Wh/km
UF-Weighted AC Electric Energy Consumption	45 Wh/km	48.1 Wh/km
UF-Weighted WTW Petroleum Energy Use	204.4 Wh PE/km	206 Wh PE/km
UF-Weighted WTW GHG Emissions	311 g GHG/km	206 g GHG/km

* CD-CS transition triggered through switch

TABLE 9 Parameters for EEC repeated drive cycles – Basic CS Strategy

Measured Parameter	CD Cycle Value	CS Cycle Value
ICE Max Torque	100 Nm	270 Nm
EM Max Torque	200 Nm	-80 Nm*
Miles Driven	14 mi	13.84 mi
Fuel Consumption	0.4 gal	0.8 gal
Total HC	13.95 g	60.25 g
Total NOx	0.014 g	2.3 g
Total CO2	2084.05 g	4915.6 g
Total CO	228 g	548 g

* Limited by the control strategy to avoid engine stalling

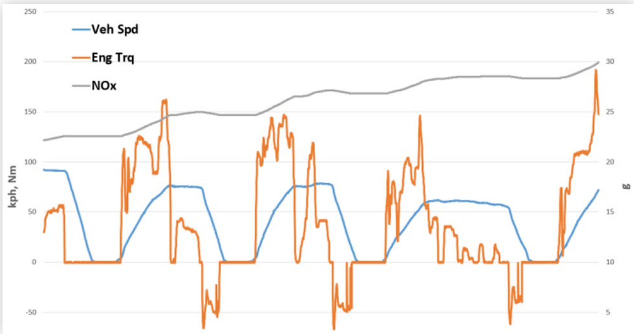
Because the engine is always running in the CD Blended Strategy (as compared to a pure EV CD strategy), and no pre-warming catalyst strategy is currently implemented in the vehicle, the emissions are a major concern. The high value for the total mass of HC produced during the CD portion of the drive cycle is expected due to the engine cold start. In [3] the author discusses how fuel optimization techniques can have negative impacts on tailpipe emissions. The team OOL strategy for engine operations can be regarded as a “high engine-loading” strategy: for this strategy consistent high engine loading can produce higher NOx emissions even when the engine and catalyst are at operating temperature. In addition, transient torque requests on the engine (in particular high torque requests) generate a considerable amount of emissions at the tailpipe.

Figure 9 shows how under CS Mode the cumulative NOx emissions increase due to high engine torque transients during hill 3 to hill 5 of the EEC drive cycle.

To reduce the amount of NOx emissions the team has been refining the engine torque request strategy by ramping in the engine torque during transients, while trying to achieve a satisfactory brake specific fuel consumption.

Second Testing Session: Optimized CS Strategy Beginning from a cold start and with an SOC of

FIGURE 9 NOx emissions during torque transients



98%, the team vehicle was tested in Blended CD Mode (clutch engaged) and Optimized CS mode over the EC3 Emission and Energy Consumption (EEC) drive cycle. The CS Mode strategy tested included the "Engine Charge" sub-mode and the "Motor Assist" sub-mode. When the vehicle is driven in Engine Charge mode, the ICE operates on the OOL and recharges the ESS SOC to the upper SOC window limit (23%). Once the upper limit has been reached the Motor Assist mode is entered: in this mode the EM provides the majority of the torque, while the ICE operates on a "minimum engine OOL". This minimum OOL has been identified through simulations to achieve the best tradeoff between BSFC and emissions. Figure 10 shows the two consecutive EEC cycles driven. The ESS SOC depletion over the cycles is reported along with the ICE fuel consumption.

In total 22.3 miles were driven in CD Blended mode. The CD Blended strategy is the same used during the previous testing session. After the vehicle fully depletes the ESS usable energy (around 3200 sec) it automatically transitions to CS Mode - Engine Charge. This transition happens during the highway portion of the drive cycle: as shown in Figure 11 when this mode is entered the torque distribution between EM and ICE changes completely. Within the CS mode the bias is towards producing torque with the ICE which operates on the OOL, while charging the ESS (if residual torque is available after the driver power request has been satisfied). The EM operates as a generator (torque has a negative sign) until the ESS is recharged to its pre-determined upper limit (23%). Once the limit has been reached (around 3400 sec) the vehicle shifts to CS Mode – Motor Assist. This mode operates similarly to the CD Blended mode: the EM is the main source of torque, while the ICE operates on the minimum OOL. A dedicated transition between the two CS sub-modes ensures that the ICE and the EM torque is increased/decreased adequately in order to meet the driver request while avoiding sudden variations that could result in excessive vehicle jerk and torsional stress on the powertrain components.

During the test it was noticed that there was a substantial amount of engine torque variation in the last part of the Engine Charge mode. This variations are observable in Figure 11 in the interval between 3300 and 3400 sec, and are caused by an incorrect torque request algorithm developed within the HCU code, which did not account for the noise on the SOC signal: the frequent variations of the SOC signals triggered continuous transitions between two torque request functions. By implementing hysteresis within the transitions the team was able to avoid the frequent torque variations observed during the previous test. The second repetition of the EEC cycle was tested again, and the ESS was re-charged to the same SOC level (51%) to allow for easier comparison. Figure 12 shows the ICE and EM torque request with the adjusted algorithm for the same part of the EEC drive cycle.

Table 10 shows the VTS results for the two consecutive EEC cycles driven using the Optimized CS Strategy. A comparison of the results with the Basic CS Strategy is also shown.

The results have been compared with those calculated for the Basic CS strategy. When comparing the results for the two

FIGURE 10 WSU vehicle driven on EEC repeated drive cycles

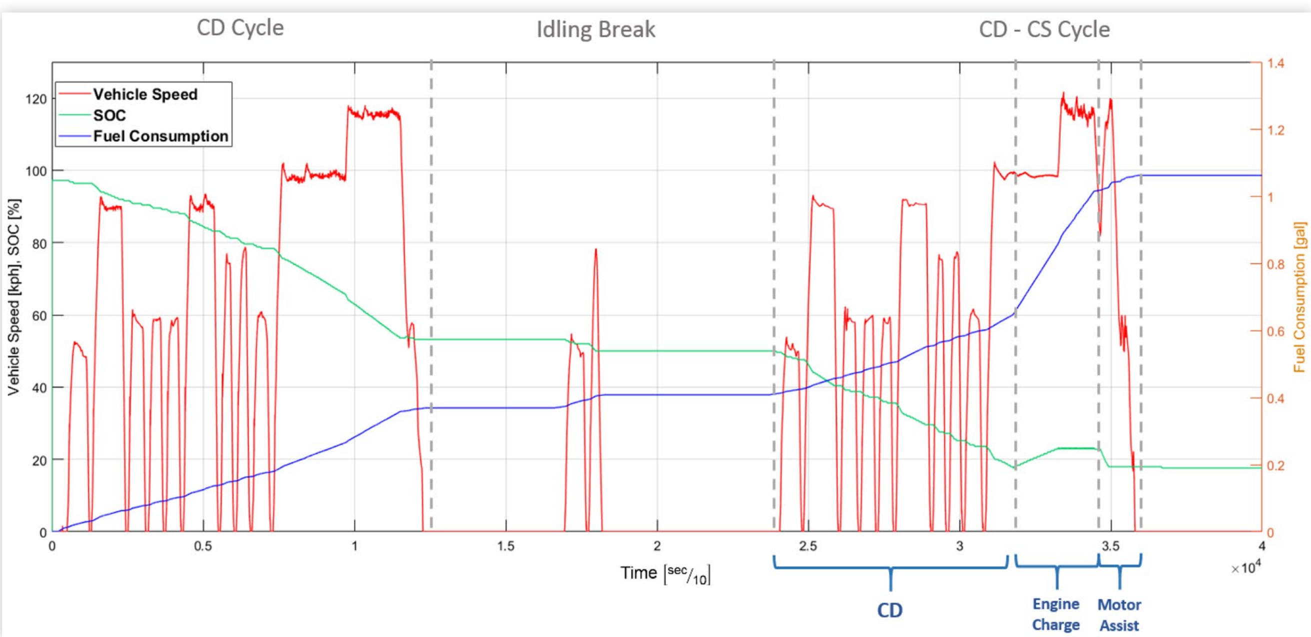


FIGURE 11 Motor and ICE torque on repeated EEC cycles.

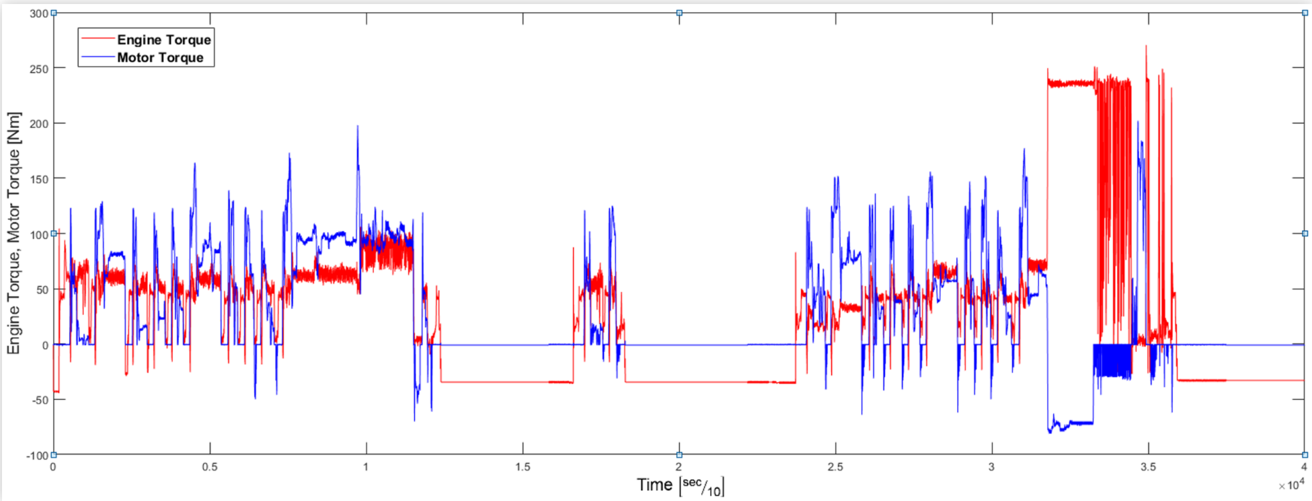
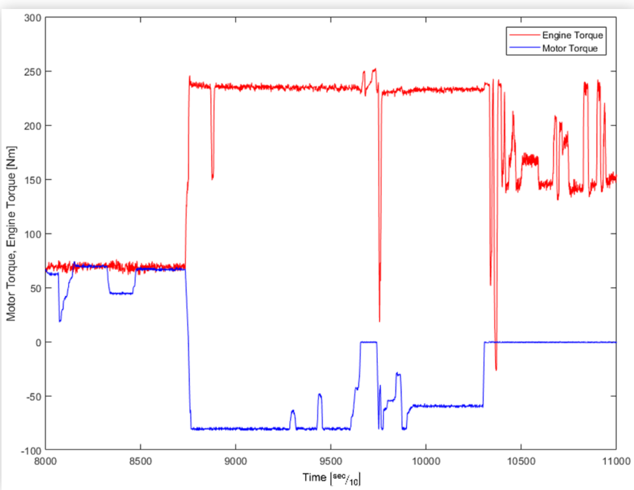


FIGURE 12 Motor and ICE torque with hysteresis implemented



strategies it must be highlighted that the CS portion driven under the Optimized Strategy is shorter than the CS portion driven under the Basic Strategy. This is due to the fact that for the latter the transition CD-CS was triggered artificially through the switch, and therefore it happened earlier in the cycle, resulting in a longer CS portion. The dynamometer room conditions have been kept constants (23 deg. C, 31% humidity), and the maximum EM and ICE torque obtained in the two cases are comparable, as observed in Table 9 and Table 11. Table 11 shows the effect of the Optimized Strategy on the overall emissions. The results show a general improvement on the emissions, in particular for the NOx. This can be attributed to the fact that the uprating and derating algorithms have contributed to the reduction of the engine torque oscillations events.

Figure 13 to Figure 16 reports the ICE operational points over the various emissions maps for the EEC cycle repetitions conducted with the Optimized CS strategy. The point time

TABLE 10 Calculated VTS for EEC repeated drive cycles – Optimized CS Strategy

Specification	Target	Actual Value	Comparison with Basic CS
Fuel Consumption	0.98 gal	1.06 gal	Improved (-16%)
Total Miles Driven	30 mi	29 mi	N/A
CD Mode Range	26 mi	22.3 mi	N/A
Utility Factor (UF)	N/A	0.429	Improved
CD Mode Total Energy Consumption	497 Wh/km	631 Wh/km	Worsened (+16%)
CD Mode Electrical Energy Consumption	137 Wh/km	207 Wh/km	Worsened (+30%)
CD Mode Fuel Energy Consumption	360 Wh/km	425 Wh/km	Worsened (+10%)
CS Mode Total Energy Consumption	670.8 Wh/km	913 Wh/km	Improved (-1.5%)
CS Mode Fuel Energy Consumption	660.5 Wh/km	903 Wh/km	Stable
CS Mode Electric Energy Consumption	10.3 Wh/km	13.2 Wh/km	Stable
UF-Weighted Total Energy Consumption	23 mpgge	18.7 mpgge	Improved (-5.6%)
UF-Weighted Fuel Energy Consumption	430.7 Wh/km	698 Wh/km	Improved (-6.6%)
UF-Weighted WTW Petroleum Energy Use	190 Wh PE/km	194 Wh PE/km	Improved (-6.2%)
UF-Weighted WTW GHG Emissions	313 g GHG/km	214 g GHG/km	Improved (-3.7%)

density (yellow dots) shows how with this strategy the ICE operates within the low emissions areas for the majority of the time. Note that some of the operating points shown in the plots below indicate operational values that are outside of the engine capabilities (i.e. 250 Nm of engine torque at 2000 rpm engine speed). These points are the results of measurement noise and should not be regarded as actual engine operating points.

TABLE 11 Parameters measured for EEC repeated drive cycles – Optimized CS Strategy

Measured Parameter	CD Cycle Value	CS Cycle Value	Comparison with Basic CS
ICE Max Trq	100 Nm	260 Nm	-
EM Max Trq	200 Nm	200-80 Nm	-
Miles Driven	14 mi	13.76 mi	-
Fuel Cons	0.38 gal	0.65 gal	Improved (-18%)
Total HC	7.92 g	20 g	Improved (-67%)
Total NOx	0.002 g	0.047 g	Improved (-97%)
Total CO2	1996.8 g	3314.3 g	Improved (-32%)
Total CO	210.26 g	434.04 g	Improved (-20%)

FIGURE 15 ICE Operating points on the NOx Map

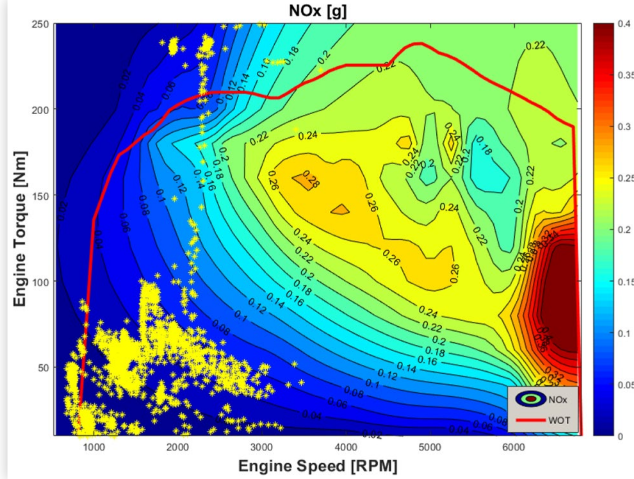


FIGURE 13 ICE Operating points on the HC Map

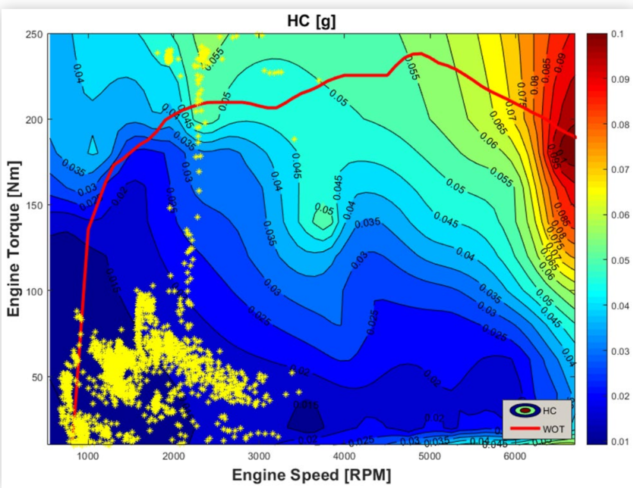


FIGURE 16 ICE Operating points on the CO_2 Map

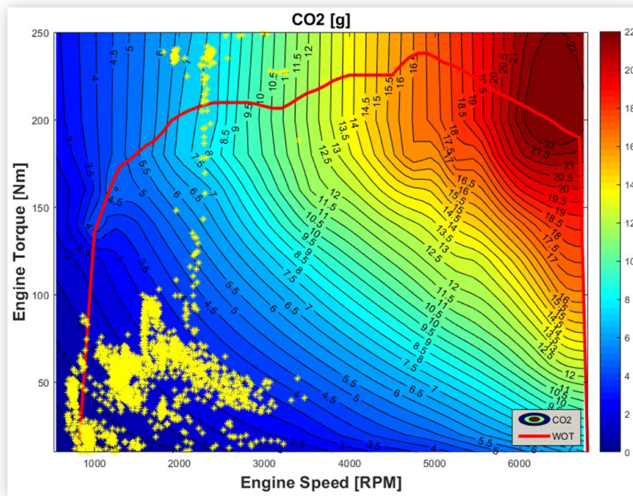
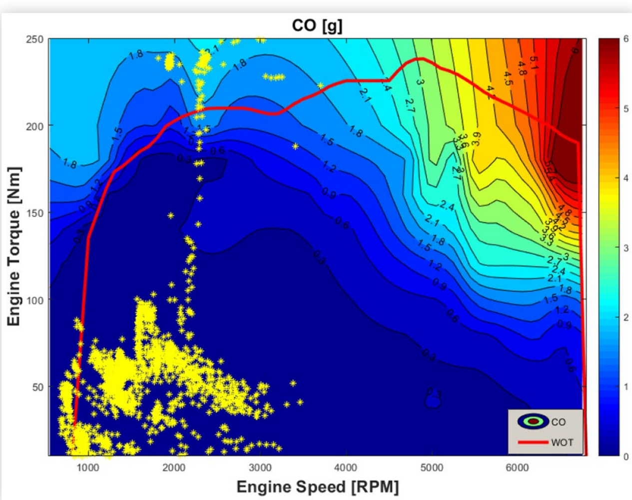


FIGURE 14 ICE Operating points on the CO Map



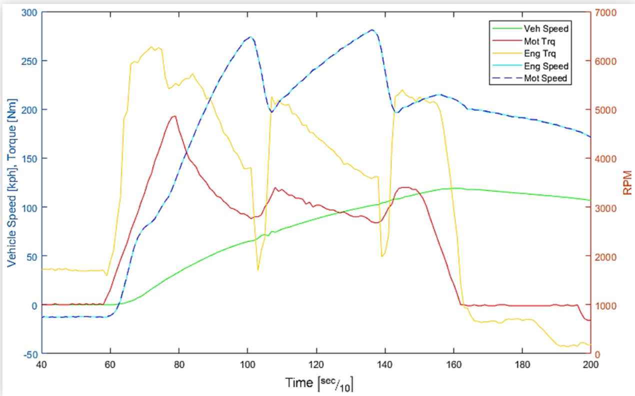
On-Road (Closed-course) Testing Results

The section presents and discusses the results obtained during the tests conducted on the Closed-course drag-racing track, for the vehicle VTS performance parameters.

Acceleration Test (IVM-60 mph) Figure 17 shows the results for the IVM-60 mph acceleration test conducted on the drag-racing track. The graph shows a full power acceleration under the Sport Mode. As mentioned earlier, the WSU vehicle is designed with a downsized 2.4 L engine compared to the stock 3.6L V6 engine. However, the introduction of the EM on the drivetrain allows for fast torque delivery during acceleration events.

The data shown in the graphs below are direct measurements obtained from the vehicle CAN buses measured at a rate of 10 Hz. Note that the vehicle speed is reported in kph instead of mph

FIGURE 17 WSU vehicle 0-60 mph acceleration

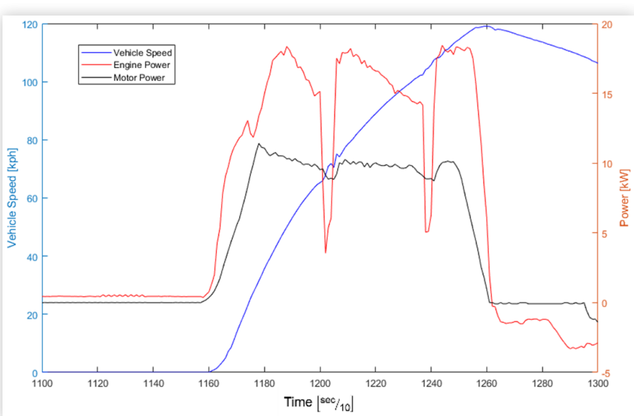


During the acceleration test the engine-disconnect clutch between the engine and the electric motor is always engaged, and therefore the ICE and EM speeds are always matching.

Gear shifting is evidenced by the ICE and EM accelerating speeds during transmission clutch opening and decelerating speeds when the transmission clutch is re-engaged. The transmission remains in first gear until the vehicle speed is 75 kph with fully pressed accelerator pedal (APP=100%). The shift from second to third gear happens at approximately 100 kph and full APP. The ICE and EM torque peaks at transmission clutch re-engagement are associated with rapid speed decelerations for both ICE and EM. Note that the EM torque provides approximately 40% of the total motive torque during this acceleration cycle in a relatively consistent manner for each gear. The ESS SOC depleted 2% during this acceleration event.

Observing the same data in terms of power in Figure 18, the amount of motor assist during the vehicle launch can be estimated. The battery provides around 12 kW at the beginning of the acceleration maneuver and around 10 kW after the first 2 seconds. Note that the maximum positive EM torque request was limited to 200 Nm to avoid wheel slip during the vehicle launch and reduce the torsional stress on the powertrain couplers during the initial testing stage. Once the launch strategy for the acceleration event is fully tested and

FIGURE 18 WSU vehicle power during 0-60 mph acceleration



the data are analyzed, the limits will be relaxed to allow for higher initial EM torque.

Table 12 below reports the IVM-60 mph time obtained from the test in comparison with the competition required value and the team predicted value (from simulations).

It can be observed that although the actual value meets the competition requirements, it is 0.6 sec higher than the predicted value. This is in part due to simulation inaccuracies, and in part can be attributed to the fact that the limitations imposed on the maximum EM torque.

Acceleration Test (50-70 mph) Figure 19 shows the results for the 50-70 mph passing test conducted on the drag-racing track. This test has been conducted in Sport Mode. The engine disconnect clutch between the engine and the electric motor is always engaged, and therefore the ICE and EM speed are always matching. During this test the gear shift is executed manually through the transmission paddle shifter, and therefore earlier shifts are observable compared to the previous test. The ICE and EM decelerations corresponding to each shifting event are more pronounced than in the previous test. The same limitations imposed on the EM torque discussed for the previous test are retained here.

Table 13 below reports the 50-70 mph time obtained from the test in comparison with the competition required value and the team predicted value.

Similarly to the previous test, it can be observed that although the 50-70 mph measured time meets the competition requirements it does not match the value predicted from

TABLE 12 Team predicted IVM-60 mph time along with Competition Requirement and Measured Value

Competition Requirement	Team Vehicle Predicted Value	Team Vehicle Actual Value
7.9 sec	5.9 sec	6.5 sec

FIGURE 19 WSU vehicle 50-70 mph acceleration

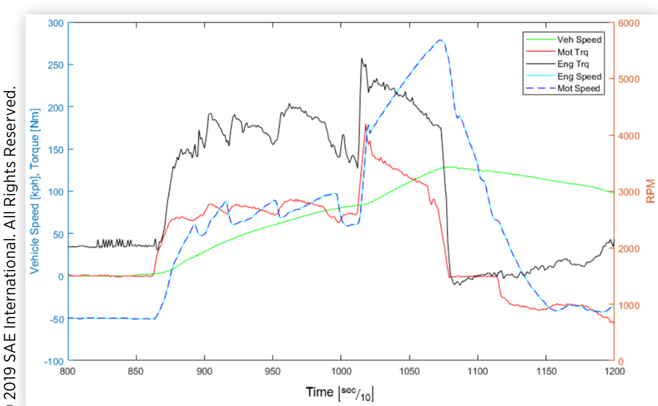


TABLE 13 Team predicted 50-70 mph time along with Competition Requirement and Measured Value

Competition Requirement	Team Vehicle Predicted Value	Team Vehicle Actual Value
9.9 sec	3.5 sec	4.5 sec

simulation. The cause for this mismatch can be attributed to the limitations imposed on the EM torque.

Braking Test The WSU vehicle uses regenerative braking to increase the overall powertrain efficiency, adopting a Parallel Braking strategy. In this strategy the friction braking is always used in conjunction with the regenerative braking when the brake pedal is depressed. Other intelligent strategies are possible, such as the Series Braking strategy with brake blending, which would allow the driver to control the torque recuperation through the brake pedal. However, this strategy would require an electronic and an external means of controlling the brake cylinder pressure, and therefore a modification of the hydraulic braking system.

Figure 20 shows the hard brake event during the 60-0 mph test. The brake pedal position (BPP) percentage and the ESS current are measured to show the contribution of the friction braking force and of the regenerative braking to the vehicle deceleration. The ESS current is recovered (positive) only for a small fraction of the event. The amount of regenerative braking is reduced as the motor speed reduces, to avoid an engine stall. During the entire test the torque converter clutch is unlocked.

Table 14 below reports the 60-0 mph distance obtained from the test in comparison to the competition required value and the team predicted value.

The value reported in the table has been extracted from logged CAN data. In order to improve the results achievable for the braking test, the team is currently optimizing the regenerative braking strategy using the MathWorks Optimization Toolbox. The goal is to identify an objective function that maximizes the energy recuperation during braking, while considering operational constraints, such as the battery SOC (to avoid charging at high amperages) and the transmission downshifting process.

FIGURE 20 WSU vehicle 60 -0 mph braking

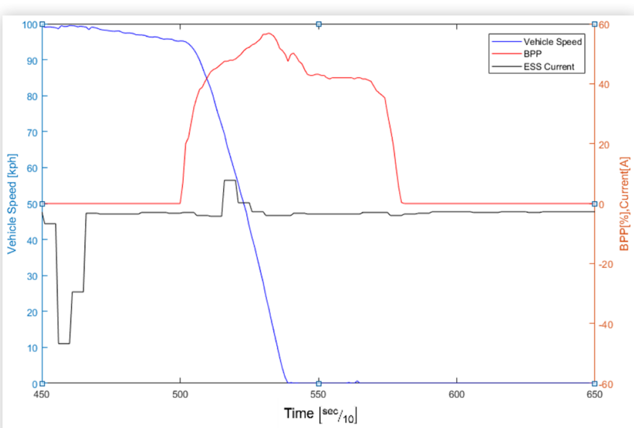


TABLE 14 Team predicted 60-0 mph distance along with Competition Requirement and Measured Value

Competition Requirement	Team Vehicle Predicted Value	Team Vehicle Actual Value
135 ft.	131 ft.	147 ft.

Handling Test The handling test was conducted on a paved parking lot available within the drag-racing facility. The space available allowed for an 80 ft. constant radius circle. The test was conducted both in the clockwise and counterclockwise directions. Figure 21 shows the results obtained over the test performed in the clockwise direction. It is assumed that all measurements refer to the vehicle's center of gravity.

Table 15 below reports the lateral acceleration value, averaged over the two tests, in comparison with the competition required and the team predicted values.

The results presented in Table 16 show that the maximum speed that the vehicle is able to achieve in either direction is 47-48 kph.

The maximum lateral acceleration that was maintained without leaving the skid pad is 9.22 m/s^2. The results show that, in a clockwise direction, the car reached its cornering limits at 47 kph, and in a counter clockwise direction it reached its cornering limit at 48 kph. In both directions, the vehicle lost traction at 49 kph. It should be stressed that the test was conducted on a circle with a smaller diameter than required and with a non-professional driver. Therefore the vehicle was not pushed to its traction limits. The good results obtained for the maximum lateral acceleration are attributed to the close to stock front to rear mass distribution of 51/49 (FR/RR).

FIGURE 21 WSU vehicle handling (Clockwise)

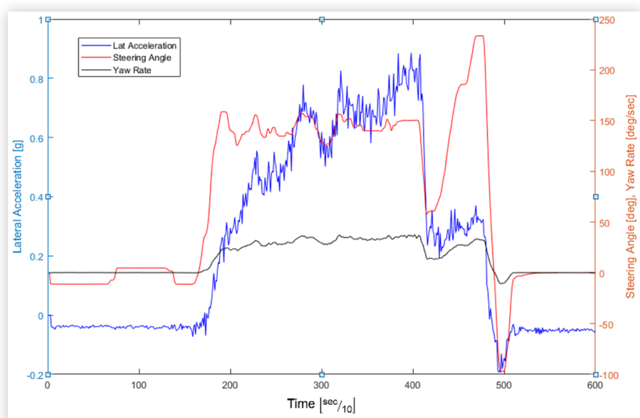


TABLE 15 Team predicted maximum lateral acceleration along with Competition Requirement and Measured Value

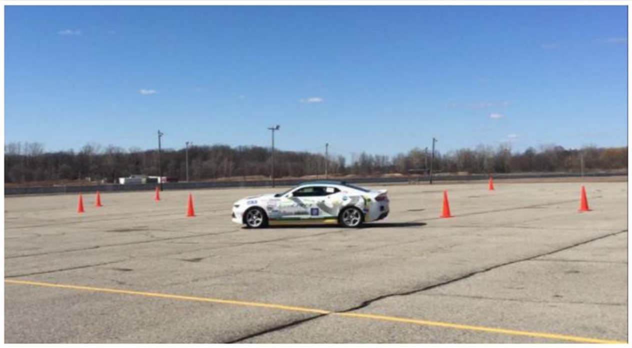
Competition Requirement	Team Vehicle Predicted Value	Team Vehicle Actual Value
0.8 G	> 0.8G	0.94 G

TABLE 16 Handling event results summary

Clockwise		Counter-Clockwise	
Speed (kph)	Stay Inside Corridor? (Y/N)	Speed (kph)	Stay Inside Corridor? (Y/N)
44	Yes	44	Yes
46	Yes	46	Yes
49	No	49	No
47	Yes	48	Yes

© 2019 SAE International. All Rights Reserved.

FIGURE 22 WSU vehicle during handling test



Conclusions and Future Work

During the fourth year of the EcoCAR 3 Competition the WSU team tested the control strategies designed for the Pre-Transmission Parallel PHEV vehicle. The tests presented in the paper have been conducted at the TRC Emission Laboratory chassis dynamometer facility, and on a team selected closed-course track.

The main vehicle operational modes have been tested on a variety of drive cycles commonly used in industry to evaluate the vehicle performance within each operational mode. The dynamometer chassis testing has been used to evaluate the emission and energy consumption performance of the vehicle. The closed-course track test has been dedicated to investigate the operational modes that require high performance to meet the driver demand, such as hard acceleration, hard braking and vehicle handling. The results obtained during the various stages of testing have been used to refine and optimize the control strategies and achieve an optimal tradeoff between energy consumption, performance and safety.

The comparison between the Optimized and the Basic CS strategies shows that there is a general improvement, in particular for the fuel consumption and for the VTS parameters related to fuel usage. This is due to the fact that the Optimized CS strategy allows the engine to operate on a minimum BSFC map by delivering the extra torque with the EM. Therefore the EM contributes more to the torque delivery when compared with Basic CS strategy. This, as expected, results in a higher electrical energy consumption. There are however margins of improvement: by optimizing the engine OOL with a numerical method, such as the MathWork Optimization Toolbox, a different operating line can be established by taking into consideration the need of limiting the electric energy use. Once a new engine OOL is determined, new tests will be necessary to verify that this operating line can be used without encountering physical limitations, and to understand if a better tradeoff between fuel and electrical energy has been achieved. The emission data show a general improvement, in particular for the total NOx value: this can be attributed to the introduction of the uprating/ derating algorithms to reduce of the engine torque oscillations events.

The results obtained during the tests conducted on the Closed-course drag-racing track show a small discrepancy for the Acceleration and Braking values compared to the results obtained from simulations: this is in part due to simulation and plant models inaccuracies, and in part can be attributed to the limitations imposed on the maximum EM torque to avoid wheel slip at the launch stage. The small degree of regenerated ESS current observable in Figure 20 is due to the initial limitations imposed on the charging process even for low ESS SOC. Once these limits are relaxed the test will be repeated with different starting SOC to understand the amount of energy that can be recuperated through the process. In addition the team is currently working on the optimization of the regenerative braking algorithm using advanced numerical optimization methods.

References

1. Di Russo, M., Zhang, Z., Wu, H., Della Porta, K. et al., “Modeling, Simulation and Control Development of a Pre-Transmission Parallel E85 PHEV for the Year-1 of EcoCAR 3 Competition,” SAE Technical Paper 2016-01-1256, 2016, doi:10.4271/2016-01-1256.
2. Lohse-Busch, H. and McBryde, D., “Best Practices for Vehicle Testing and Energy Consumption Measurement,” EcoCAR 3 Fall Workshop Presentation, Sep. 2017.
3. Walsh, M.P., “Plug-In Hybrid Electric Vehicle Supervisory Control Strategy Consideration for Engine Exhaust Emissions and Fuel Use,” Master Thesis, Virginia Polytechnic Institute and State University, May 4, 2011.

Contact Information

Dr. Jerry C. Ku
at jku@wayne.edu

Acknowledgments

The authors wish to thank the Department of Energy, Argonne National Laboratory, General Motors, other Eco CAR 3 competition sponsors, and all members of WSU Eco CAR 3 team for supporting our competition project.

Definitions/Abbreviations

ANL - Argonne National Laboratories
APP - Accelerator Pedal Position
AVTC - Advanced Vehicle Technology Competition
BSFC - Brake Specific Fuel Consumption
CD - Charge Depleting
CS - Charge Sustaining
DOE - Department of Energy
EEC - Emissions and Energy Consumption
EC3 - EcoCAR 3

ECM - Engine Control Module
EM - Electric Machine
ESS - Energy Storage System
GHG - Greenhouse Gas
GM - General Motors
HCU - Hybrid Control Unit
HIL - Hardware in the Loop
HV - High Voltage
ICE - Internal Combustion Engine
IMG - Integrated Motor Generator
IVM - Initial Vehicle Movement
MCU - Motor Control Unit
MIL - Model in the Loop
OOL - Optimum Operating Line
PEU - Petroleum Energy Usage
PHEV - Plug-in Hybrid Electric Vehicle
RWD - Rear Wheel Drive
SOC - State of Charge
TRC - Transportation Research Center
UF - Utility Factor
VTS - Vehicle Technical Specifications
WSU - Wayne State University
WTW - Well to Wheel

ISSN 0148-7191